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THE PRE-TERRESTRIAL HISTORY OF METEORITES.

THE completion of the studies for students relating to the composition and structure of meteorites, which have recently been published in this JOURNAL, furnishes an opportunity for me to record certain deductions which seem to me warranted by the facts there presented, but which, being largely theoretical, had best be stated as the expression of individual opinion.

That theories of the origin and cosmic history of meteorites have been propounded before, and that these have varied widely in character, the present writer is well aware. These theories may be mentioned at the outset, together with the names of those who have given them special support, without, however, entering into any discussion of the merits of each.

Meteorites have been declared to be (1) terrestrial matter discharged into space by the volcanoes of the earth and returned to it again (Sir Robert Ball); (2) matter discharged from the volcanoes of the moon (La Place, J. Lawrence Smith); (3) matter ejected from the sun (Sorby); (4) portions of shattered stars (Meunier); (5) portions of a shattered planet (Boisse); (6) portions of comets (Newton); (7) clouds of gas or dust cemented and solidified by the action of the earth's atmosphere (Brezina).

All of these hypotheses have been urged by men of eminence, each urging strong reasons for his views. These reasons can be learned by study of the original authorities, and the discussion of them in the present article is not a part of my purpose. I shall endeavor here simply to present my own views and my reasons for the same.

The study of meteorites has shown that:

1. The majority of iron meteorites are octahedral.
2. The majority of stone meteorites are chondritic, and contain considerable glass.
3. Between iron and stone meteorites there is every gradation — they are formed of the same sort of matter.

The above statements would probably not be questioned by any authorities of the present day. The following, however, might not be agreed to by all:

4. The substance of meteorites was in a solid state before the fall of these bodies to the earth.

5. The structure of the majority of meteorites shows that their substance has cooled from a liquid or semi-liquid condition to that of a solid.

6. The structure of the majority of iron meteorites shows that the change from a liquid or semi-liquid to a solid state has taken place slowly.

7. The structure of the majority of stone meteorites shows that the change from a liquid or semi-liquid to the solid state has taken place rapidly.

The four latter statements may then be briefly discussed, and important known objections to them stated.

Concerning statement 4: It was suggested by writers in the early part of the last century that meteorites were concretions formed in our own atmosphere. Brezina inclines to accept this view with the modification that the substance of meteorites was extra-terrestrial, but that it arrived at the earth in the shape of gas or dust and was cemented or solidified by the earth's atmosphere. To my own mind, the slickensided surfaces and veins exhibited by many meteorites afford sufficient contradiction of such a view, and compel the conclusion that the matter in which such structures occur had existed in a solid state for a considerable length of time before it reached the earth.

Concerning statement 5: Several writers, but especially Daubree,[1] have expressed the conviction that the substance of meteorites gives evidence of having passed directly from a gaseous or vaporous state to that of a solid. The opinion seems to be based chiefly on Meunier's synthetic experiments, in which he succeeded in reproducing mineral aggregations having the composition of meteorites and somewhat resembling them in structure, by the inter-action of vapors.[2] But, as pointed out by Cohen,[3] the absence of gas and vapor pores in meteorites

[1] "Observations sur les conditions qui paraissent avoir preside a la formation des meteorites," *Comptes Rendus*, 1893, CXVI, pp. 345-7.

[2] *Encyclopedie Chimique*, Tome II, "Meteorites," chap. v.

[3] *Meteoriten-kunde*, Heft I, p. 327.

argues against such an origin of their substance, and further, Fouqué and Lévy produced by cooling from fusion, mineral aggregates as closely resembling meteorites as those made by Meunier from vapors. Again, the crystalline structure of the minerals of meteorites perfectly resembles that of terrestrial minerals known to be produced by cooling from fusion.

Concerning statement 6: That the complete crystalline structure possessed by the great majority of iron meteorites indicates a lapse of time sufficient for a slow, uniform arrangement of the molecules of their mass, in other words a slow cooling, has rarely been doubted. Such a conclusion certainly accords with all terrestrial experience and observation. It has been suggested by Cohen,[1] however, that the crystalline structure expressed in iron meteorites by the Widmanstätten figures may be really a sort of skeleton growth, similar to that seen when needles of ice form over the surface of rapidly cooling water, and that hence the Widmanstätten figures may indicate a rapid crystallization. It is unfortunate that no attempt to reproduce Widmanstätten figures artificially in iron has ever yet succeeded, for if this could be done valuable evidence for judgment on this point could be secured.

Taking the evidence as it stands, however, and especially taking into consideration iron meteorites like that of La Caille, whose structural features show a complete parallelism throughout a large entire mass, the indications seem to me to point strongly to slow crystallization. Certainly analogies between the formation of crystals in iron and in water should be drawn with hesitation. Iron is far more viscous than water and movement in it would take place slowly. Further, the crystalline plates of meteoritic iron differ in composition, showing that time must have elapsed for separation of ingredients as has not taken place in the ice formed upon water.

Concerning statement 7: This opinion is based chiefly on the large quantity of glass found in most of the chondritic meteorites, which, it is to be noted, make up by far the larger quantity of known stony meteoritic matter. Glass is known to indicate rapid cooling. Further, the character of the chondri themselves is such as to lead many students of the subject, notably Brezina and Wadsworth, to believe that they are the result of rapid and arrested crystallization. The fact that chrysolite, the least fusible and therefore the earliest cooling mineral, forms the most chondri, lends support to this view. It must be confessed that the real origin of chondri is as yet very obscure and the theory above suggested is far from accounting for many of their peculiarities. Yet the facts above noted seem to me to argue more strongly in favor of a rapid cooling of the substance found in such meteorites than a slow one.

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[1] *Meteoriten-kunde*, Heft I, p. 326.

If the arguments in favor of the above statements seem sustained, then the conclusion to which they appear to me to point is the following: *Meteorites are portions of a disrupted mass of cosmic matter which had a spheroidal form, increased in density toward the center, and cooled from a liquid or semi-liquid to a solid state before disruption.*

The application of this hypothesis to the subject in hand may perhaps best be traced by applying it in a reverse order. Given a defined quantity of liquid or semi-liquid. It will take the form of a spheroid, since this is the only form known in which a liquid mass would maintain itself in space. Its materials would arrange themselves according to density. The iron, for example, would sink to the center, and the slag-like silicates rise to the surface, as they may daily be seen to do in a blast furnace, or as a centrifugal separator assorts substances according to density. The exterior of the sphere owing to contact with the cold of space would be cooled with comparative suddenness, giving the minerals of the surface a glassy, brittle character. The protected interior would cool more slowly, giving the molecules of the metallic center an opportunity to arrange themselves in an orderly, crystalline fashion. In time, however, the globe becomes solidified from center to circumference. During the process of solidification, and later, many processes of disruption and adjustment go on as the result of strains of various kinds, record of which is to be found in the structure of meteorites. Fissures will be formed, into some of which pasty metallic matter will be forced from below, and which will, in its passage upward, enclose angular fragments of the siliceous crust. Other fissures occurring only in the siliceous portion of the globe will give rise to the formation of quantities of angular fragments, which will be cemented together again by pressure to form breccias. Such fissures would be comparatively large, and affect a considerable area of the globe. Other minor fissures would form in ramifying networks, which would be filled by adjacent substance penetrating in a more or less liquid form. Differential movements of solid portions, without the existence of fissures, would produce slickensided surfaces. Finally, the progressive disruption of the body occurs. To produce this, two or three forces may be appealed to. In the first place, there is the familiar fissuring from shrinking and contraction as the body passes from the liquid to the solid state. It is perfectly evident that a certain amount of this is taking place upon the earth.[1] Meunier suggests further, that in the moon we can see this process extended as much farther as the moon is more fully cooled than the earth, and he regards the well-known bright streaks of the moon as enormous fissures (*rainures*) showing a progressive disruption of its mass.[2] While few probably at the present day would accept this interpretation of the bright streaks of the moon, there are numerous other indications that the moon is considerably fissured. Meunier also points to the asteroids as an illustration of a dismembered heavenly body.

In the second place, strains corresponding to the tidal strains of the earth would produce a constant disruptive effect; and, in the third place, the recent investigation of Professor Chamberlin,[3] has shown how the fragmentation of a small body may take place by near approach to a large one.

Once the body is broken up, its fragments may be drawn out into the form of a somewhat attenuated swarm or cluster. The possibility of the subsequent capture of single portions of such a cluster by the earth can hardly be denied. The character of the portion captured, in respect to its structure, density, and composition, then, will depend on the position it occupied in the globe of which it formed a part.

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[1] See CHAMBERLIN, "On a Possible Function," etc., JOUR. GEOL., Vol. IX, No. 5.

[2] *Cours de Géologie Comparée*, pp. 258 *et seq.* [3] *Op. cit.*

That meteorites exist in such swarms in space seems very probable from a recent investigation of Högbom.[1] Plotting the known meteorite falls according to the days of the year, he has discovered undoubted and significant groupings. Thus of the nine known howardites, three fell during the first days of August, and three during the first half of December. The probabilities are stated to be several thousand to one against such an occurrence being a mere coincidence. Again, of the three known eukrites two fell June 13–15. The chances are said to be ninety to one that these had a common origin. There are numerous other groups brought out on the chart so made, which seem to point to the existence in space of meteorite clusters met on the same date by the earth in its annual revolution. The probabilities seem sufficiently in favor of the existence of such clusters to warrant placing some reliance in the constitution indicated for them. Thus with the group of August howardites previously mentioned are associated one siderite and three chondrites; with the December howardites, one siderite, one bustite, one chladnite, and a number of chondrites. The constitution indicated for these swarms resembles therefore, to a remarkable degree, that called for by the hypothesis here advocated, especially when it is remembered how exceedingly fragmentary must be evidence based on the few meteorites seen to fall. A similar constitution has been also exhibited at times in the substance of a single meteoric shower. A notable case is that of Estherville, which contained all gradations, from iron to stone meteorites.

Two or three other points of evidence may be noted as tending to show that, in such a globe as that assumed, the substances were arranged in order of their densities and that it had at some time a hot interior and cold exterior.

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[1] *Bull. Geol. Inst. of the University of Upsala*, Vol. V., Part 1.

The first is drawn from our knowledge of the crystallography of iron. According to modern metallographists, iron occurs in three allotropic modifications known as alpha, beta, and gamma irons. When heated to a temperature not higher than 700° C., iron remains in what is known as the alpha state; from 700 to 860° C. it assumes the beta state, and from 860° C. to the melting point, the gamma state. In cooling, from the melting point, for instance, the iron does not necessarily return through these modifications, but remains in the state which it assumed at the highest temperature.[1] Now gamma iron crystallizes in octahedrons, while alpha and beta iron crystallize in cubes. The majority of meteoritic iron is plainly octahedral in structure. It is hard to escape the conclusion, therefore, that it has been heated to a temperature at least as high as 860° C., and, further, that the cubic irons, some of which occur among meteorites, have been subjected to a somewhat lower degree of heat. The latter, it is true, must be cooled and reheated to a somewhat lower temperature than at first to have their structure accounted for on this theory. But this could quite reasonably occur, and their relative quantity is so small as to make them of minor importance.

A second corroborative fact is that the carbonaceous meteorites are of exceptionally low specific gravity. Now the carbonaceous meteorites are those which contain hydrocarbons which could not exist under any high degree of heat. Such meteorites could not have experienced any sensible heating subsequent at least to the formation of these hydrocarbons. But the low density of these meteorites would place them, according to the hypothesis, on the outer surface of the spheroid, where, after the first solidification from cooling, little further heating would be encountered.

A third corroborative fact is found in the existence of diamonds in the iron meteorite of Cañon Diablo, a meteorite which exists in quantity amounting to several tons. Such diamonds have been produced by Moissan by heating to a high temperature iron saturated with carbon and allowing it to cool under pressure. This is exactly the process through which the substance of an iron meteorite would pass if formed according to the above hypothesis. The other meteorite known to contain diamonds, Nowo-Urej, is also one which would have formed not far from the metallic center of such a globe, as it contains large metallic veins and by some is classed among the iron-stone meteorites.

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[1] F. OSMOND, *The Metallographist*, July, 1900.

The hypothesis outlined above may ask the special attention of the geologist, on account of the suggestions it may offer regarding the history of the earth. If it be true that meteorites are fragments of a broken-up globe, it is not unlikely that they show to us, to some extent, the constitution of our own globe. Uniformity of cosmic matter has been indicated by all studies of meteorites, as well as by all spectroscopic inquiries into the chemistry of space. Uniformity of cosmic history seems therefore probable also.

I have shown in the studies previously referred to that meteorites chiefly differ in composition from the crustal terrestrial rocks with which we are familiar in having an excess of iron, nickel, and magnesium, and in being practically without free silica, oxygen, and water. Assuming that the earth, however, has passed through a history like that of the globe above hypothesized, the absence of iron, nickel, and magnesium[1] from its crust is explained by the conclusion that they have been carried within its interior by their density. They are therefore removed from our observation, except as occasional outflows such as that known in Greenland bring them to view. It is well known that the density of the earth as a whole requires that its interior contain matter of higher specific gravity than that with which we are familiar upon its crust, and it has often been suggested that this matter may be iron and other metals. The alternative supposition is that the matter of the interior may be like that of the crust but has become denser through condensation and pressure.

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[1] Magnesium is here referred to not as the element, which is relatively light, but as the essential constituent of chrysolite, which is of high specific gravity and forms some of the heaviest terrestrial eruptive rocks.

The free silica of the earth's crust is readily accounted for if we remember that the rocks of the earth's crust have been *worked over*, while in meteorites they are seen in their primitive condition. When silicates are exposed to the action of carbonic acid for any length of time the bases change to carbonates and silica is set free.[1] It seems reasonable to suppose that the vast amount of calcium and magnesium now held as limestone was originally in the form of silicates. If the carbonic acid of the limestones should be withdrawn to the atmosphere, and their bases combine with the excess of silica of the crust, rocks as basic as those of meteorites would probably be formed.

Similarly, the lack of oxygen in meteorites may be only relative, and because much of the matter of which they are composed was in the interior, deep-seated and protected from gaseous action. The superficial, lighter siliceous portions of meteorites are found to be oxidized. It is reasonable to believe the earth's substance is not oxidized except for its superficial crust. It may be urged in support of the view that oxygen could not have been present where meteorites were formed that little or no oxygen is found among the free gases obtained from meteorites. But rocks do not seem to have the power of absorbing and holding oxygen as they do other gases. Terrestrial rocks do not contain it, although they hold hydrogen, carbon dioxide, and carbon monoxide in large quantities.[2] Yet there is no lack of oxygen in the earth's atmosphere.

The absence of water from meteorites is an important gap in the parallelism of constitution of meteorites with that of the earth. In the gases hydrogen and oxygen, which it has been shown meteorites possess, a cosmic body has the elements necessary for the formation of water. Conditions of nascence, or possibly of electricity, might exist in a body the size of the earth, which would lead to the formation of water from these gases, which might not prevail upon a body of smaller size. The chief reason, however, for the absence of water from meteorites seems to be the fact that the size of the meteorite spheroid was probably not sufficient to enable it to hold a quantity of the free gases competent to the formation of water or even to retain water vapor if it was once formed. The spheroid was probably as destitute of an atmosphere as the moon.

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[1] This fact is more fully stated by SIR JOHN MURRAY, *Proc. Roy. Soc. of Edinburgh, 1890–1*, p. 229.

[2] See *Studies*, JOUR. GEOL., Vol. IX, p. 402.

I am well aware that an origin of meteorites from a shattered globe has been suggested before. Boisse was perhaps the first to do this,[1] but the idea was especially elaborated by Meunier,[2] who reconstructed from the various types of meteorites a hypothetical globe in which these types were arranged largely in accordance with their density. But the hypotheses of these authors were based purely on considerations of density, it being arbitrarily assumed that in a cosmic body substances *would* arrange themselves according to density.

It was when a study of the structural characters of meteorites showed me that the substances *had* apparently arranged themselves in the order of their density, and exhibited corresponding differences of structure, that I was led to form the above hypothesis; and it is perhaps worth remarking that I reached this conclusion before I had seen Meunier's papers on the subject.

It is not likely that the globes or spheroids, such as have been here hypothesized, were of large size. In the solar system, for example, there is no indication that the total disruption of a body anything like in size to a planet has ever taken place. Such an occurrence would produce effects more catastrophic in their nature than could be referred to matter so small in relative quantity as that which has within human experience reached the earth in the form of meteorites. Such globes would, perhaps, in their entirety, never come within human observation. But that there exists in space a vast quantity of fragmental matter beside that visible to us as stars, nebulæ, and the bodies of the solar system, there can be little doubt.

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[1] *Memoires de la Société des lettres, sciences et arts de l'Aveyron*, Vol. VII, p. 168.

[2] *Cours de Géologie Comparée.*